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HEAT TRANSFER IN THE VICINITY OF A TWO-DIMENSIONAL PROTUBERANCE

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ABSTRACT

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Empirical equations are presented which will estimate the ratio of protuberance-to-flat plate heat transfer coefficients for supersonic flow in the vicinity of two-dimensional protuberances in a turbulent, supersonic boundary layer. The equations were derived from experimental heat transfer data taken around several two-dimensional protuberances, i.e., a 1 x 2-inch stringer, a 2 x 4-inch stringer with and without a 30-degree wedge, and a one-quarter cylinder forebody. Important parameters in the equations are boundary layer thickness, protuberance geometry, Reynolds number, and Mach number. Using the equations, the average deviation between estimated and experimental ratios is from -9 to +15 percent.

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RESEARCH AND DEVELOPMENT OPERATIONS

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DEFINITION OF SYMBOLS

Symbols	Definition
h	local convective heat transfer coefficient with protuberances
h_o	local smooth flat plate convective heat transfer coefficient
L	length from forward edge of protuberance
L'	length downstream of protuberance trailing edge
M	Mach number
y	height of protuberance
δ	boundary layer thickness
θ	defined in Figure 1

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SUMMARY

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Three empirical equations are presented for estimating the turbulent flat plate heat transfer coefficients in the vicinity of a two-dimensional surface protuberance under supersonic flow conditions. Each equation is applicable to one specific area in reference to the surface protuberance. The locations are the area forward of the protuberance, the separated flow area immediately behind the protuberance, and the area of reattached flow more than two protuberance heights behind the protuberance. The equations are limited to the vicinity of two-dimensional protuberances which have flat, cylindrically blunted, or wedge-type forward faces and a 90° flat rear face. The equations were developed from the experimental data of Burbank [3] using a dimensional analysis approach and reduced to their final form by trial and error. The increase in heat transfer coefficient is seen to be a function of boundary layer thickness, Mach number, protuberance geometry, and Reynolds number. A comparison between Burbank's experimental data for several protuberance shapes with predicted values of h/h_o from equations (1), (2), and (3) showed an average deviation of from -9 to +15 percent.

I. INTRODUCTION

In turbulent, supersonic flow, the local heat transfer coefficient for a vehicle skin with surface irregularities or protuberances can vary widely from the local heat transfer coefficient for a skin which is unobstructed. For design purposes, it would be highly desirable to be able to calculate these "altered" heat transfer coefficients knowing the protuberance geometry and the "unaltered" air flow parameters such as local Mach number, Reynolds number, and boundary layer thickness. A recent literature survey showed that an analytical method for calculating local, supersonic heat transfer coefficients around protuberances was not in existence. However, Bertram [1] showed that, for hypersonic flow, empirical equations could be formulated to predict heat transfer coefficients around protuberances. Consequently, his method of formulation was extended to the supersonic regime. The heat transfer data around two-dimensional protuberances presented in Burbank's report [3] provided excellent material for deriving the desired empirical equations.

II. TEST FACILITY AND MODELS

The experimental data given in Burbank's report were obtained from P. S. Yip's protuberance heat transfer test [3] run in Langley Research Center's Unitary Plan Wind Tunnel. Test free stream Mach numbers were 2.65, 3.51 and 4.44. Reynolds number per foot varied from 1.3×10^6 to 4.7×10^6. Three turbulent boundary layer thicknesses were achieved by mounting the test flat plate model at different locations within the tunnel test section. For thick boundary layers of six inches, the test plate was mounted on the tunnel side wall. For thinner boundary layer a splitter plate was installed in the test section. The instrumented surface was attached to the splitter plate, and the protuberances were mounted at different downstream locations giving boundary layer thicknesses over the model of 0.7 inches and 1.5 inches. Boundary layer trips were used in the splitter plate configuration to assure turbulent flow.

The two-dimensional protuberances tested are sketched in Figure 1. The basic models were a 1 x 2-inch stringer and a 2 x 4-inch stringer. Either a 30° wedge or a quarter-round cylinder could be added to the forward face of the 2 x 4-inch stringer in order to study the effects of leading edge geometry. A rather wide test plate and protuberances plus a centerline location of the heat transfer instrumentation were used in hopes of attaining and measuring two-dimensional flow. However, oil flow pictures taken at the end of the test hinted that true two-dimensional flow may not have been achieved. Therefore, the data used in deriving the two-dimensional protuberance equations may have some inherent inaccuracies caused by traces of three-dimensional flow characteristics in the flow field.

III. DISCUSSION OF RESULTS

As explained in the Appendix, dimensional analysis and a trial and error scheme to account for variable protuberance forward face configurations resulted in the following three equations for h/h_o. Upstream of the protuberance, the heat transfer coefficients can be estimated by the equation

$$h/h_o = 60.0(1.10 - .10\ \delta/y)\left[\frac{M^3}{Re\left(\frac{L}{y} + \frac{\cot\ \theta}{2}\right)(y/\delta)^2}\right]^{1/4} \qquad (1)$$

if $L/y \leq 4.0$. The cot θ term in the denominator provides a correction for two-dimensional protuberances with wedge-type faces. Local Reynolds number is calculated from the free stream properties and the wetted length to the point being analyzed. The distance, L, is measured from the forward base of the protuberance to the point in question. Heat transfer coefficients behind the protuberance are approximated by two equations, the choice of which depends on the distance, L', downstream from the trailing surface. Immediately behind the protuberance where the flow is separated, the applicable equation is

$$h/h_o = \frac{1}{4}\,(L'/y)^2 \left[1.0 + .021\left(\mathrm{Re}\,M^2\,\frac{\delta}{y}\right)^{1/8}\right] \tag{2}$$

provided $L'/y \leqq 2$. It was found that flow reattachment occurred at L'/y approximately equal to two regardless of the forebody shape. The following equation is used to estimate h/h_o in the reattached area, $L'/y \geqq 2.0$.

$$h/h_o = 1.0 + .025\ \mathrm{Re}(y/L')^2\ M^2(\delta/y)^{1/8}. \tag{3}$$

Notice that wake heating for two-dimensional protuberances is in no way affected by forebody angle.

Figures 2 through 4 show the correlation of the function

$$\left(1.10 - .10\,\frac{\delta}{y}\right)^4 \cdot \frac{M^3}{\mathrm{Re}\left(\frac{L}{y} + \frac{\cot\theta}{2}\right)(y/\delta)^2}$$

from equation (1) to the ratio of protuberance-to-flat-plate heat transfer coefficients. Accuracy of the correlation is good for Mach numbers 2.65 and 3.51. At Mach 4.44 the correlation is not nearly so good, mainly due to data scatter. Figure 5 shows the correlation of the function

$$[\mathrm{Re}\ (y/L/)^2\ M^2(\delta/y)]$$

of equation (3) with experimental h/h_o data. Again, data at Mach 4.44

show more deviation. The correlation of equation (2) with test data is best seen in Figures 6 through 17.

Figures 6 through 17 show profiles of the protuberance tested and the correlation of test data with all three equations. Reynolds number effects were so small in the separated wake of each protuberance that only one calculated line was used in each figure. Accuracy of the calculated approximations is not only best for the lower Mach numbers, but also best for the more blunted protuberances. Equation (1) should be used with caution for forebody angles less than 30 degrees, since accuracy seems to decrease with decreasing θ. Approximating a 45-degree forebody angle for the quarter-round cylinder forebody configuration (Figures 15 through 17) yields reasonably accurate results. The most critical parameters in these equations are Mach number, y/δ, and y/L. Reynolds number effects are almost negligible and would be well within the accepted scatter of the original data, i.e., ±25 percent.

Since equations (1), (2), and (3) were developed from data in the Mach number range 2.5 to 4.5, it would be wise not to extend their use to higher Mach numbers without first comparing them with experimental data. When used in this Mach number range, and for sufficiently blunt bodies, an accuracy of -9 to +15 percent can be expected in the predicted values of h/h_o.

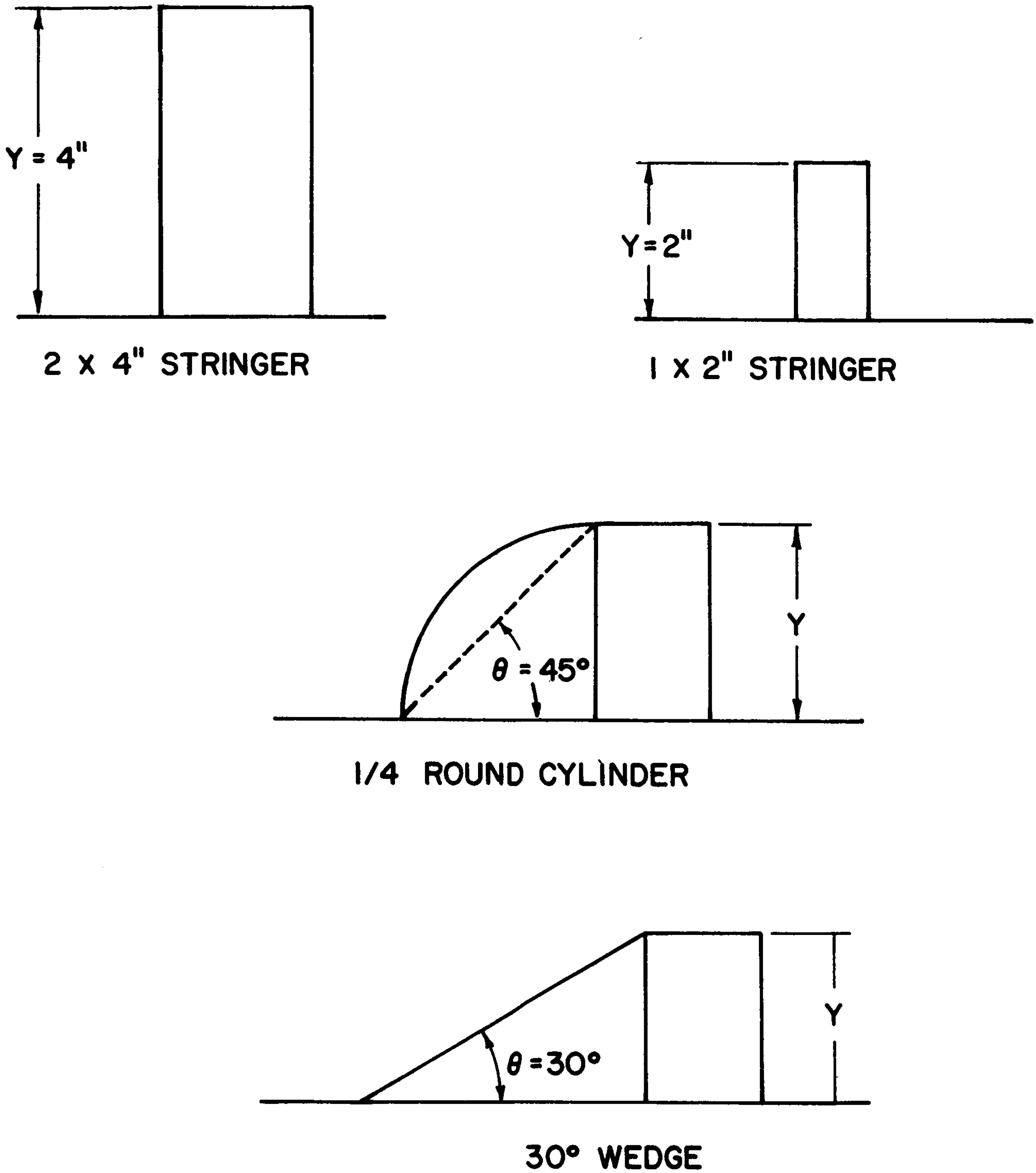

FIGURE 1. SKETCH OF PROTUBERANCE MODELS

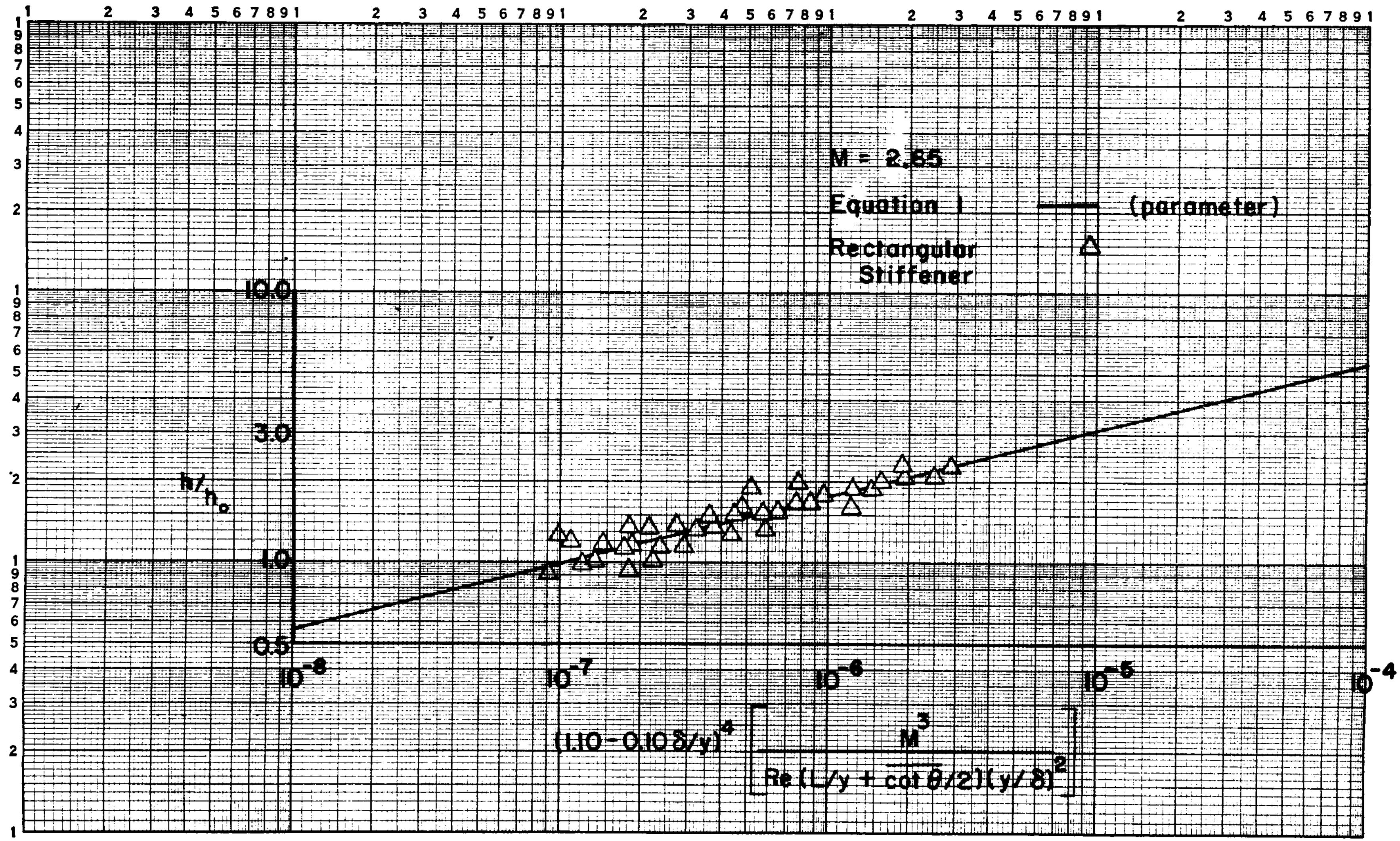

FIGURE 2. CORRELATION OF EXPERIMENTAL DATA
M = 2.65

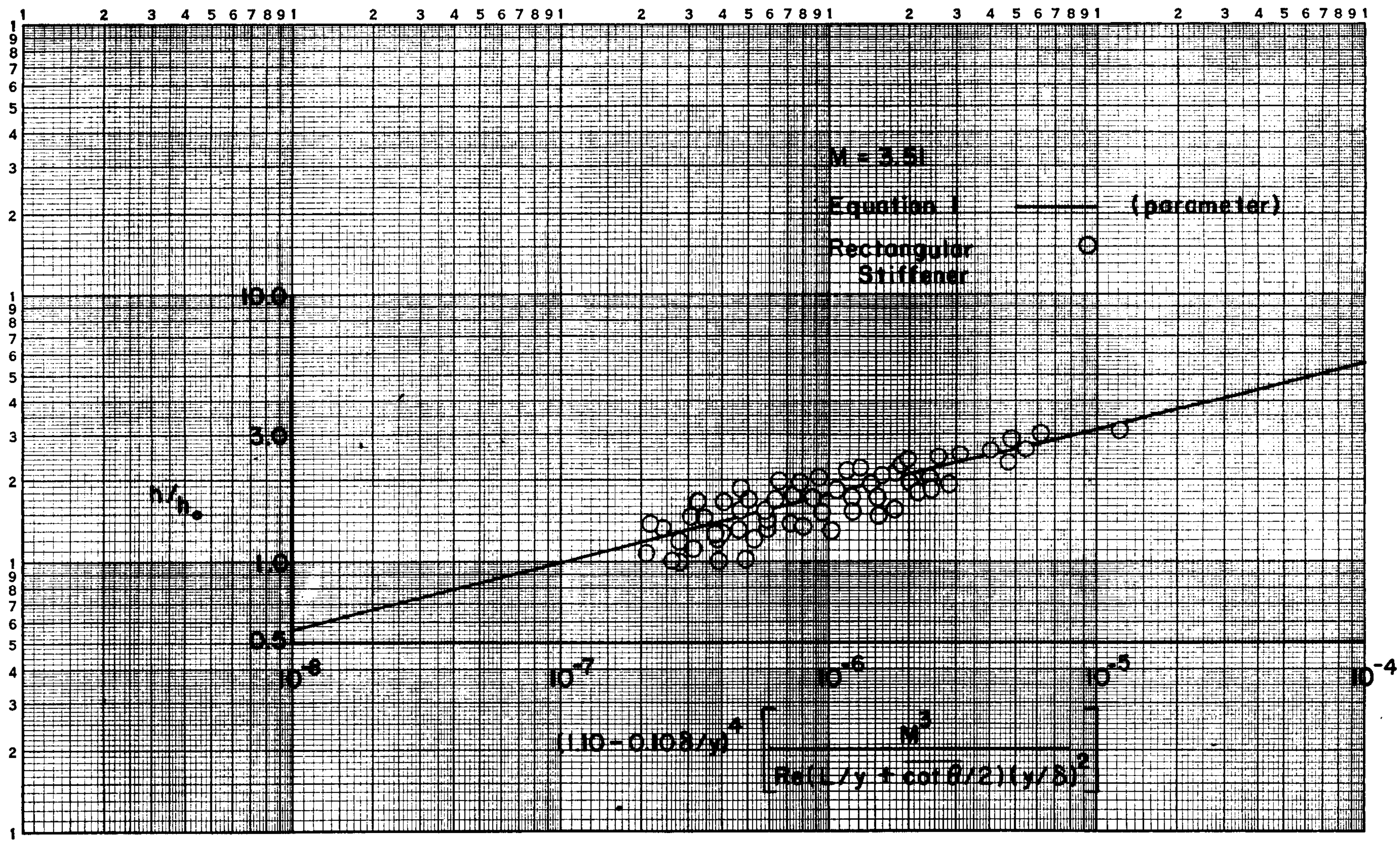

FIGURE 3. CORRELATION OF EXPERIMENTAL DATA
M = 3.51

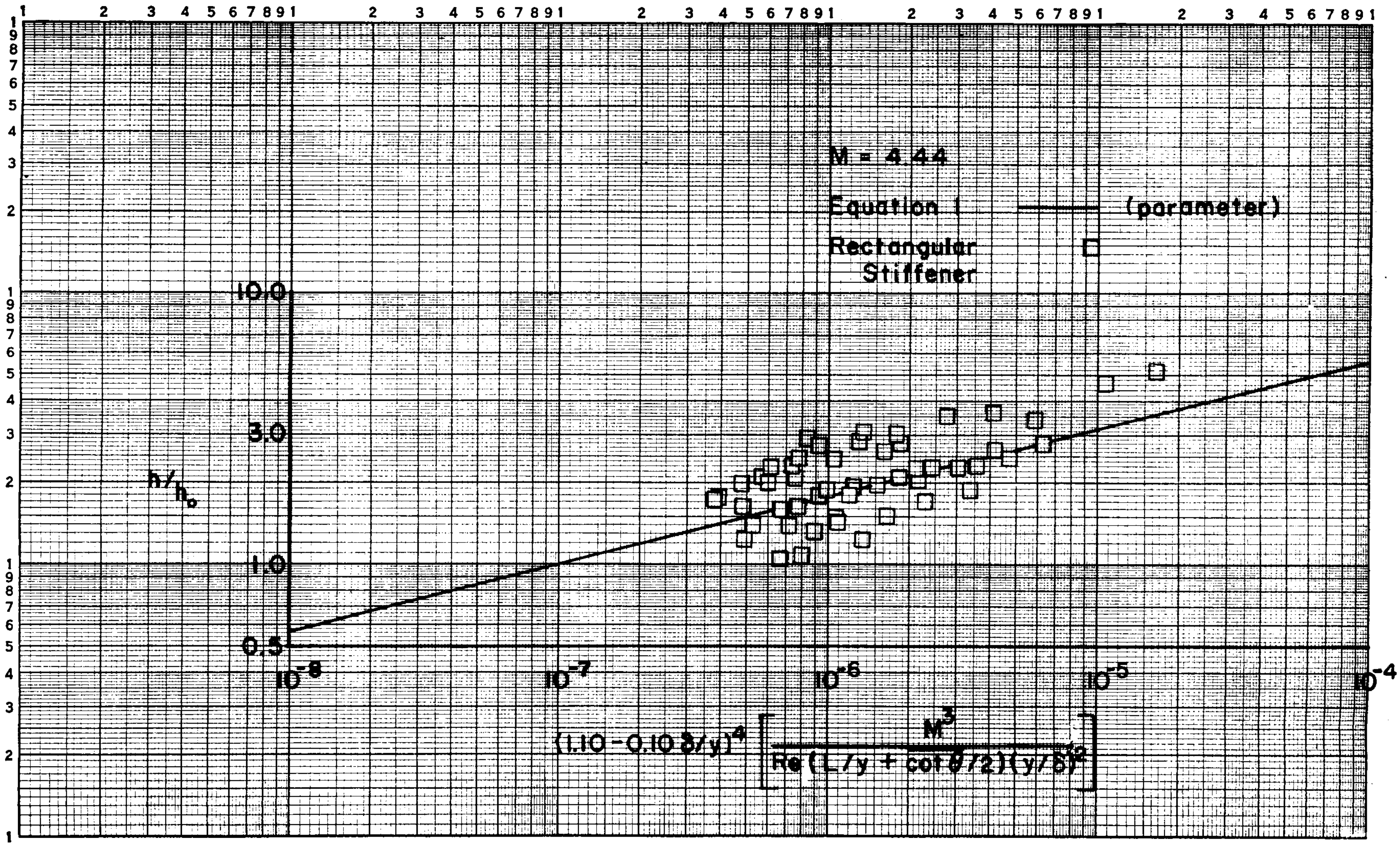

FIGURE 4. CORRELATION OF EXPERIMENTAL DATA
M = 4.44

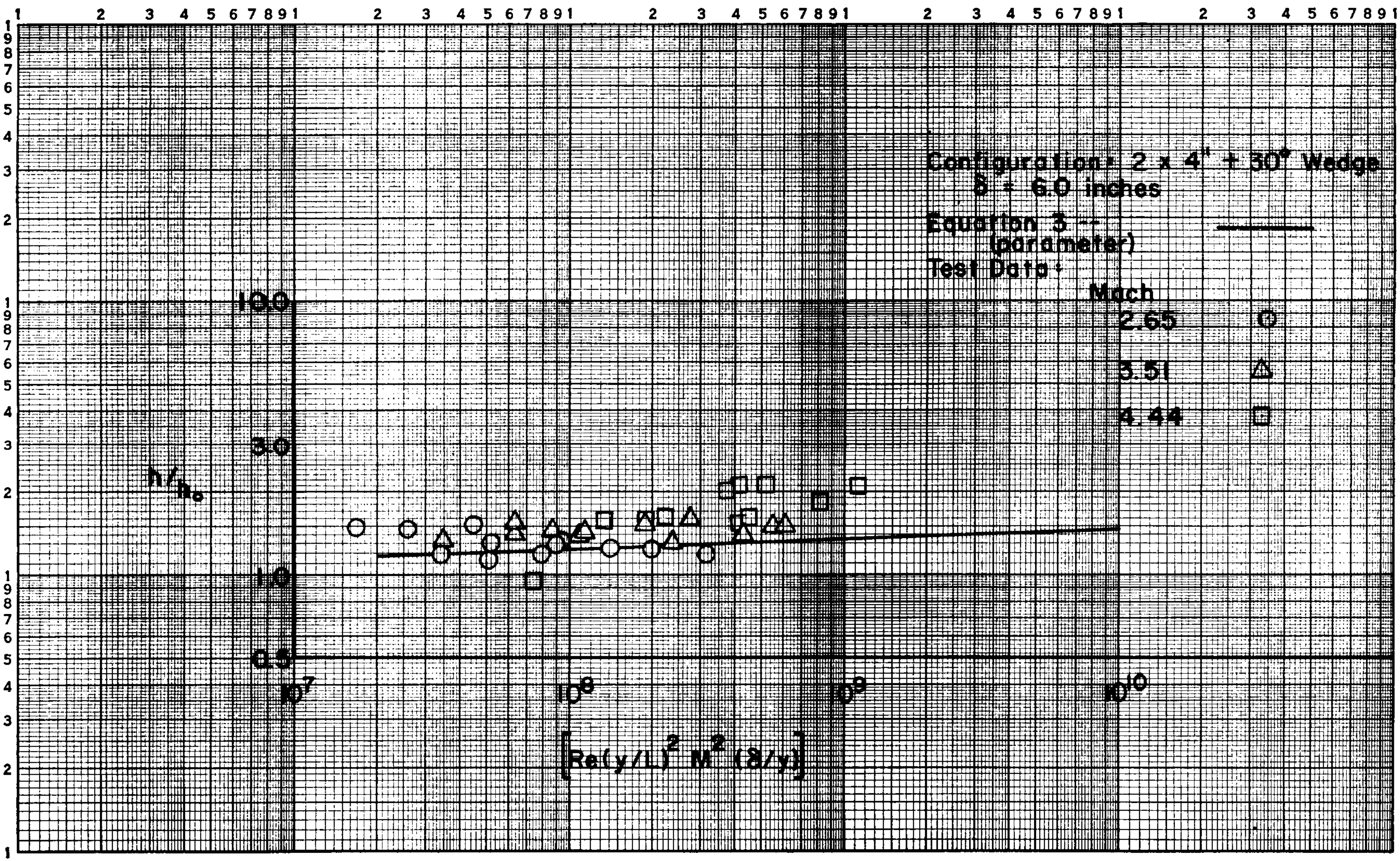

FIGURE 5. CORRELATION OF EXPERIMENTAL DATA
EQUATION 3 PARAMETER

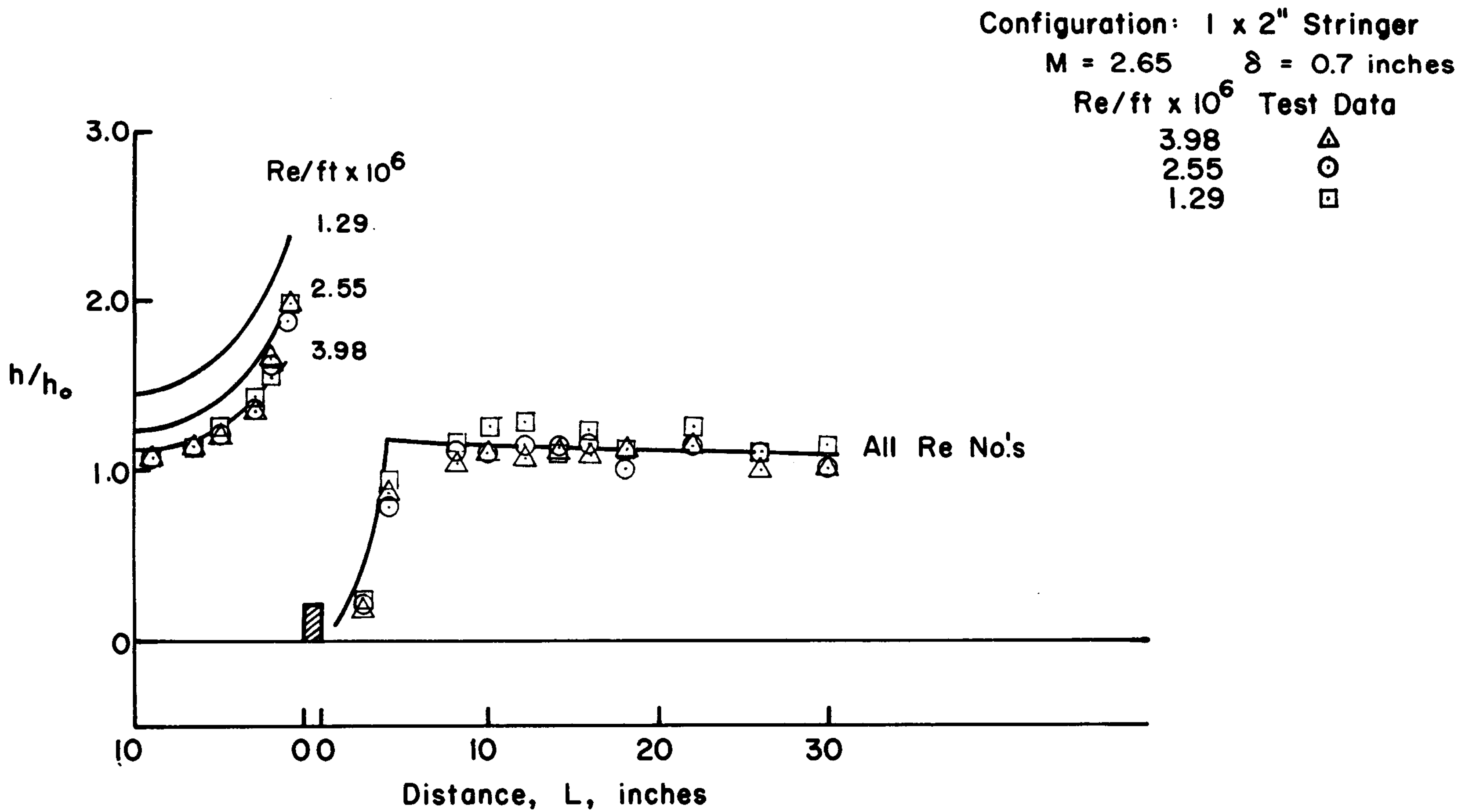

FIGURE 6. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

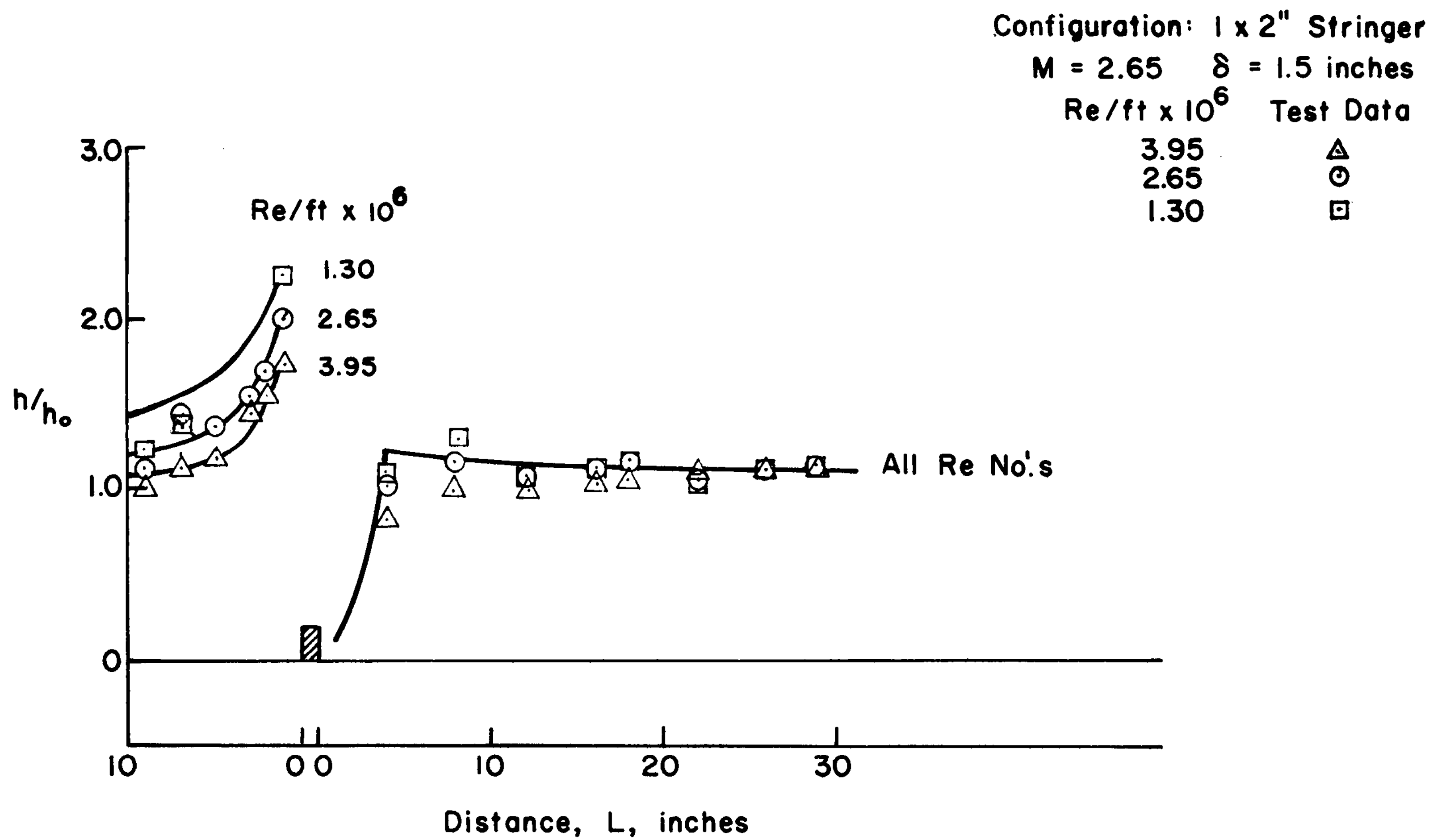

FIGURE 7. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

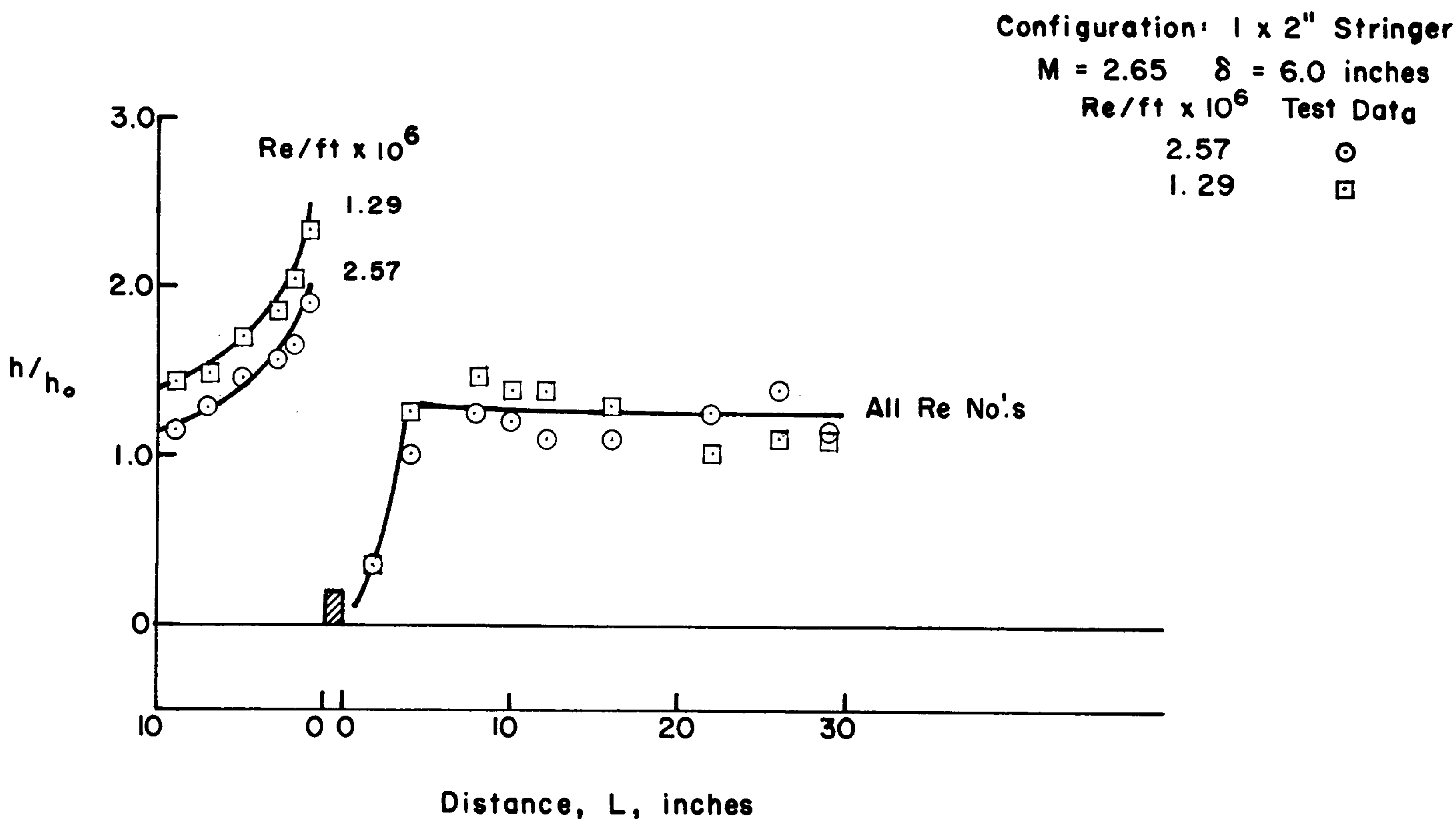

FIGURE 8. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

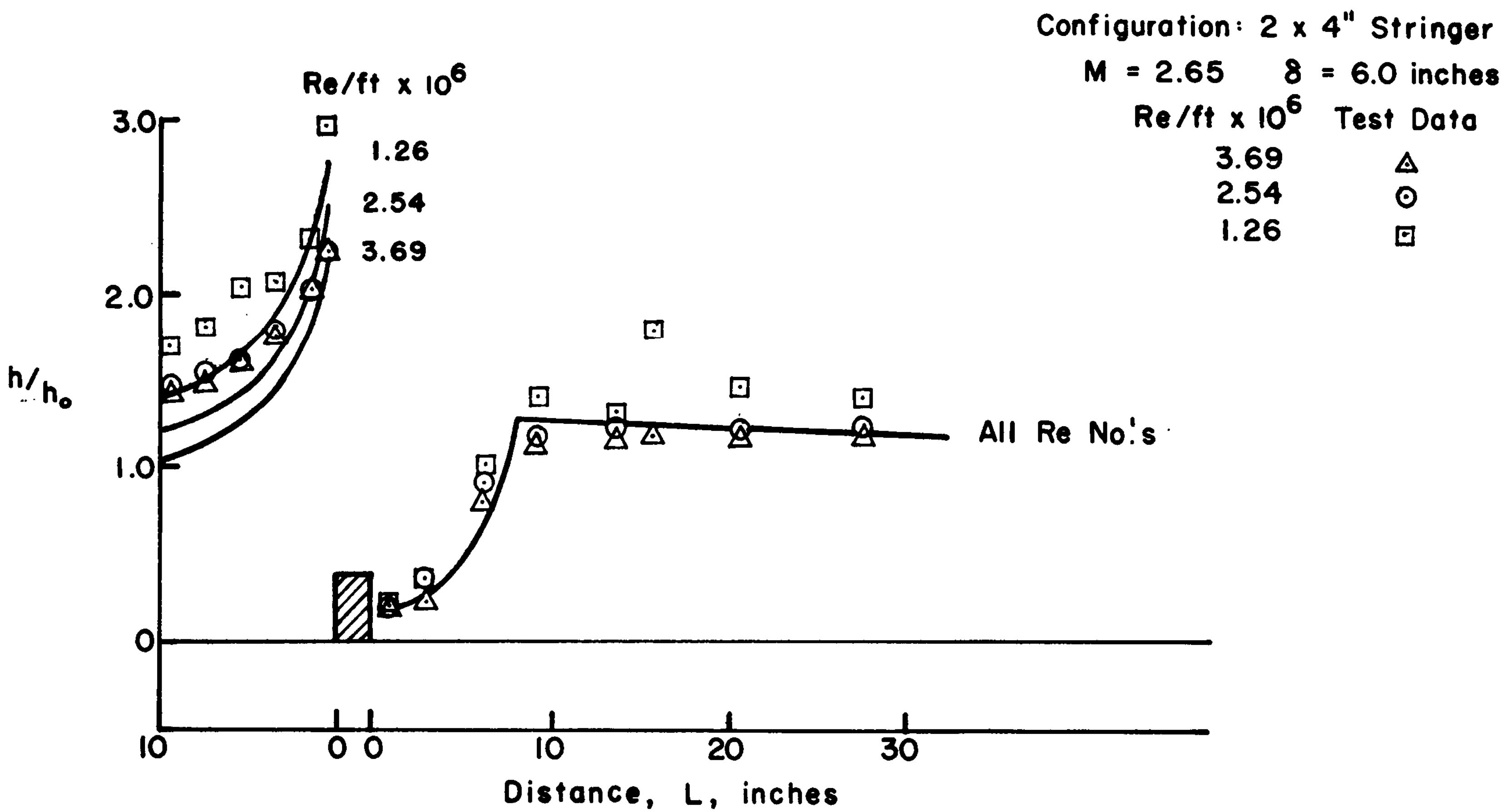

FIGURE 9. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

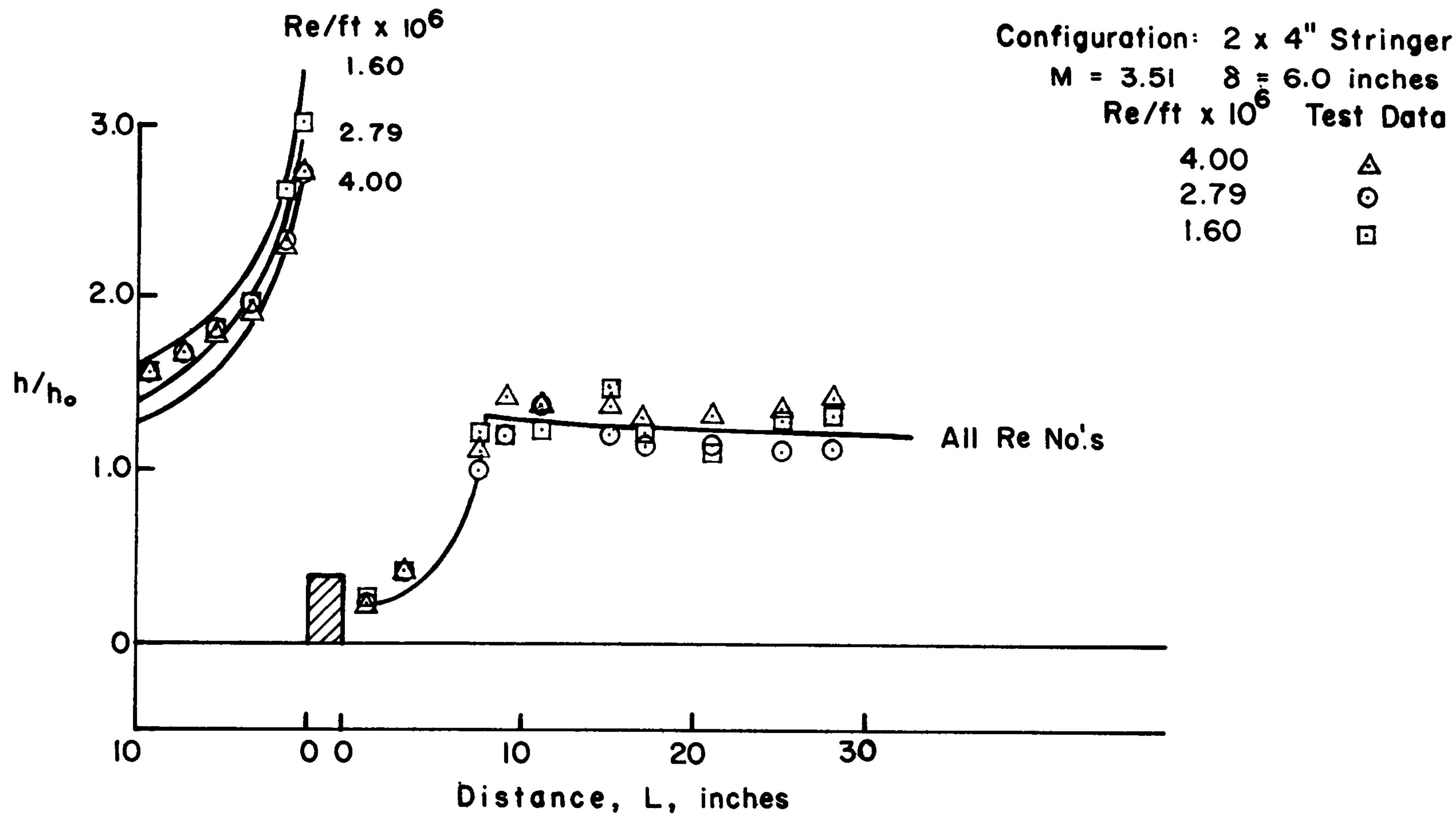

FIGURE 10. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

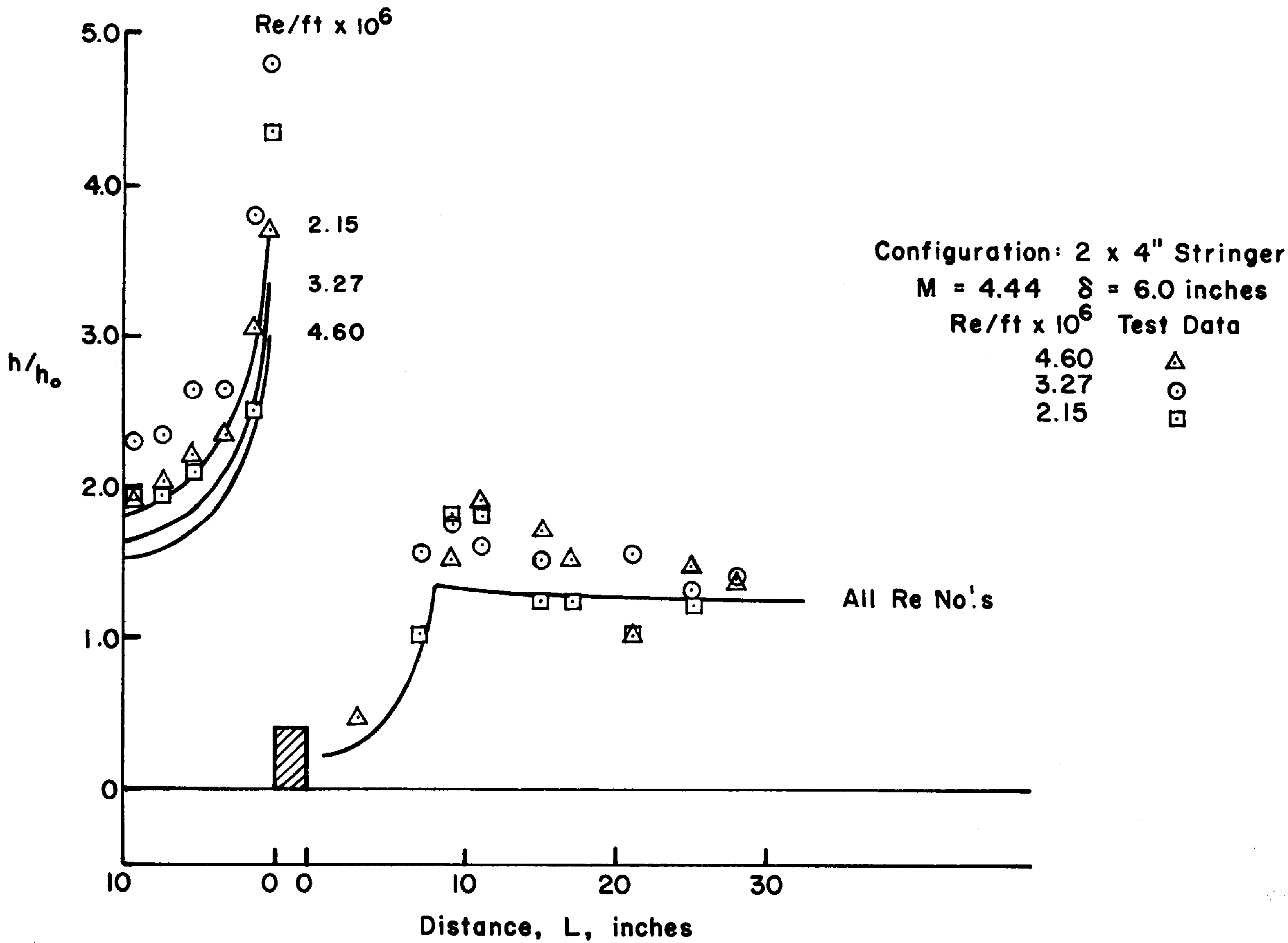

FIGURE 11. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

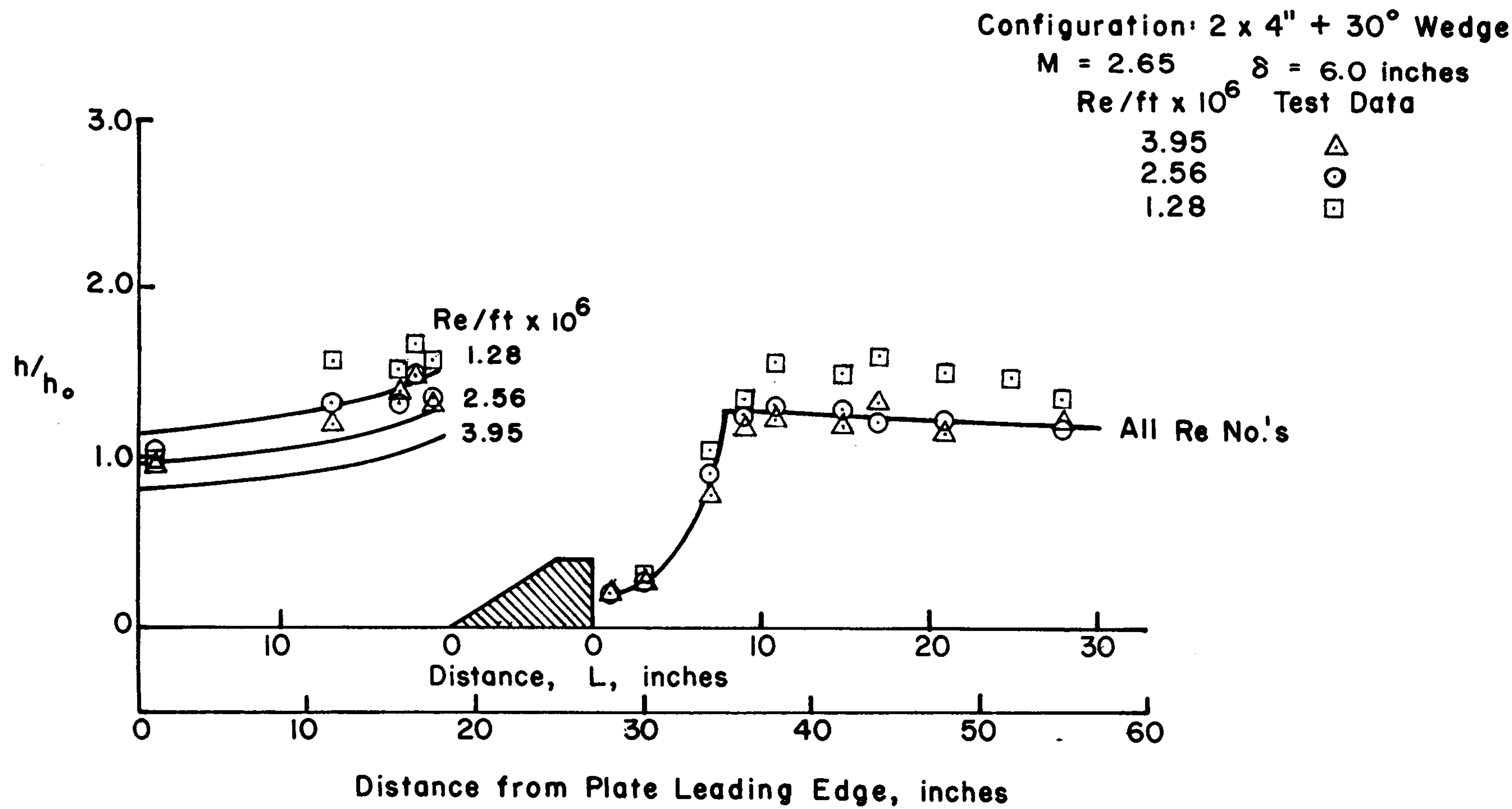

FIGURE 12. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

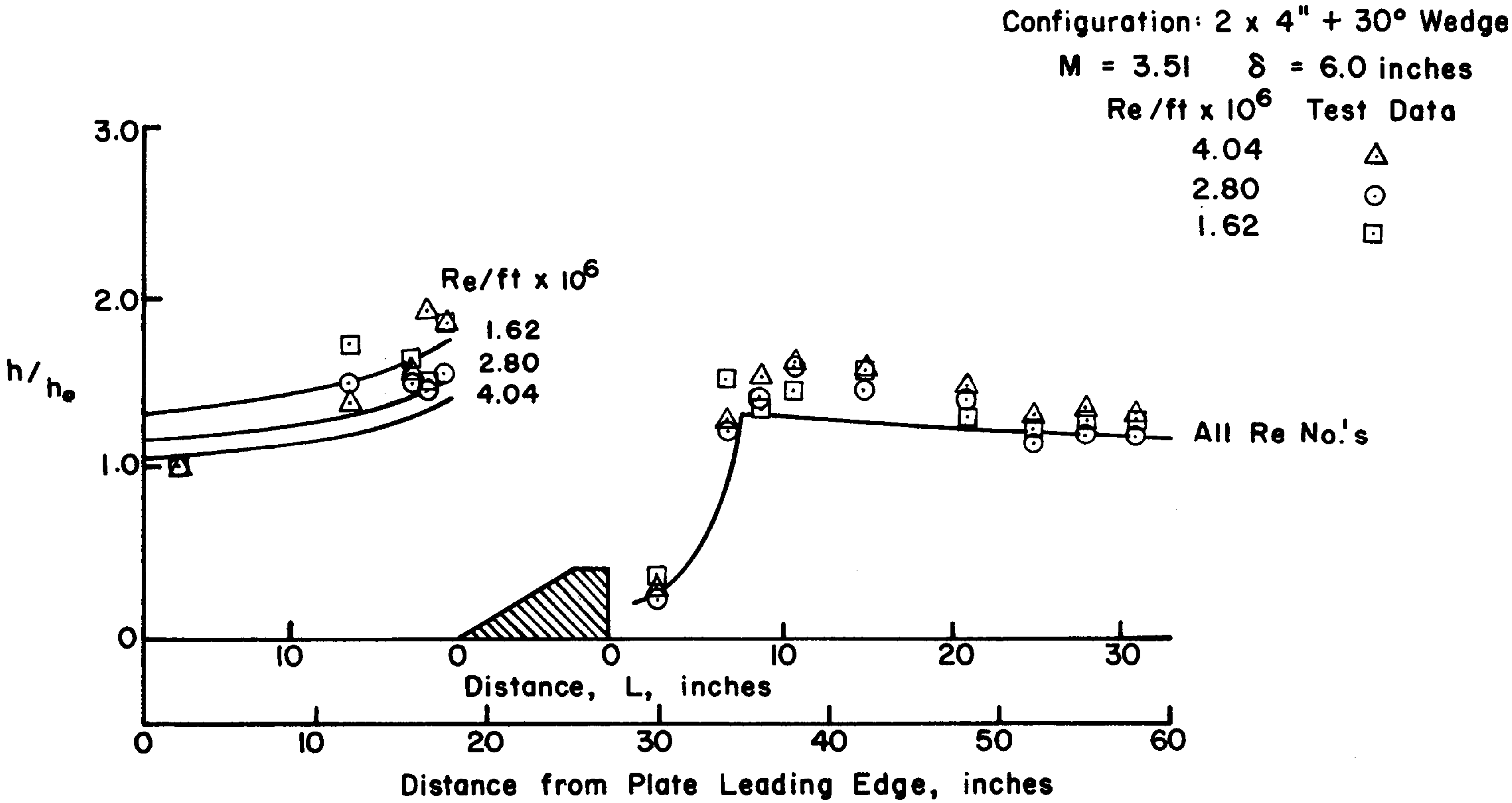

FIGURE 13. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

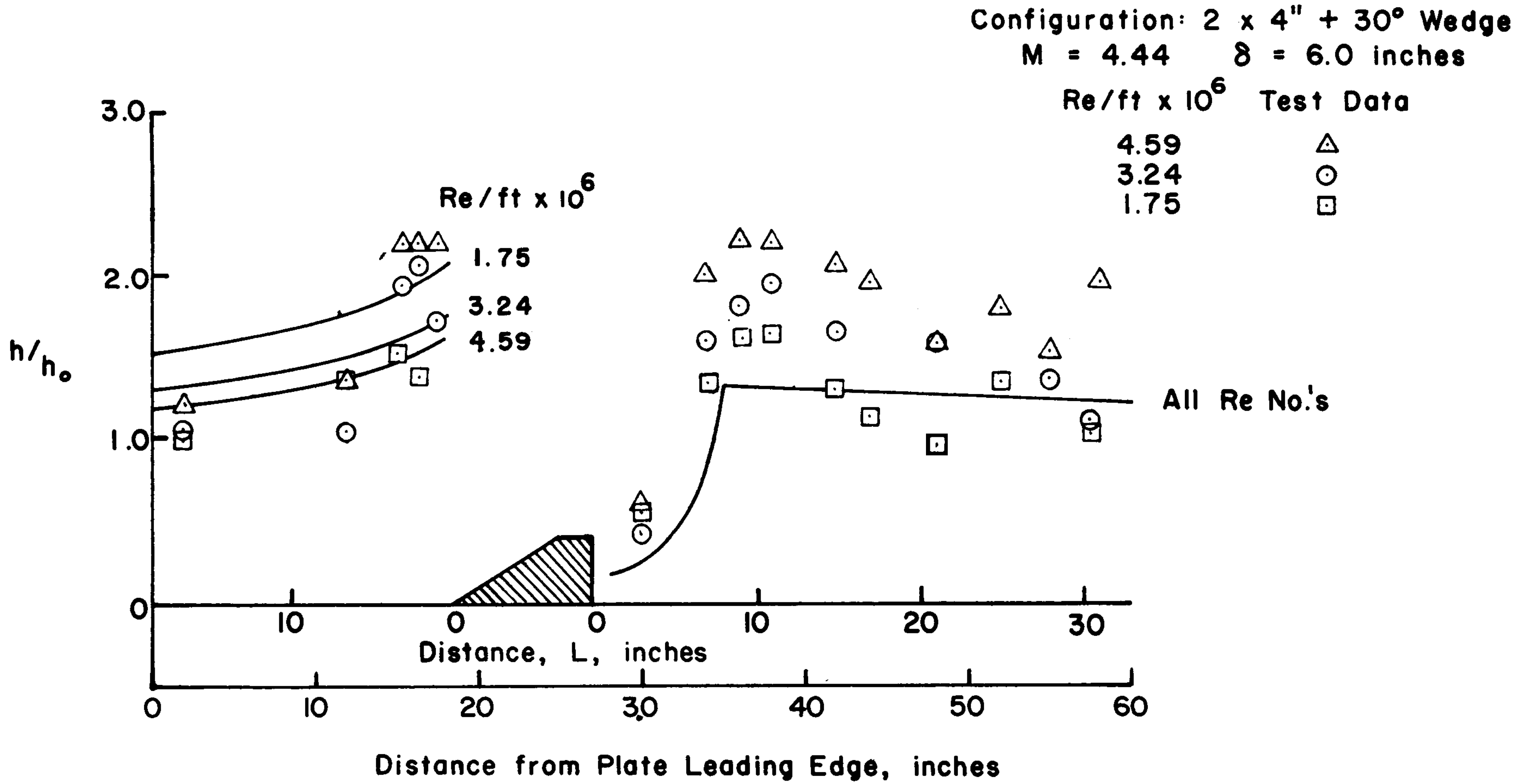

FIGURE 14. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

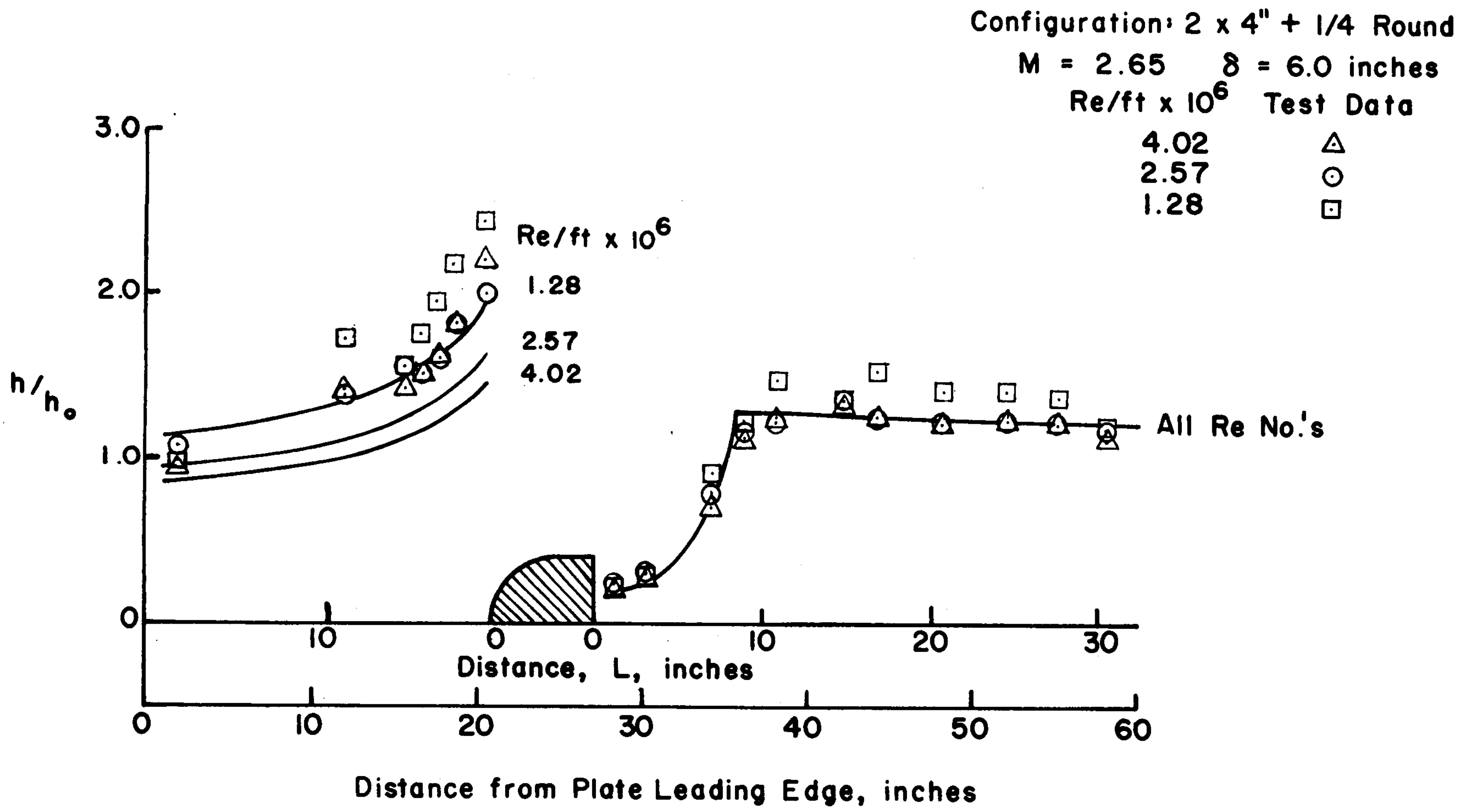

FIGURE 15. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

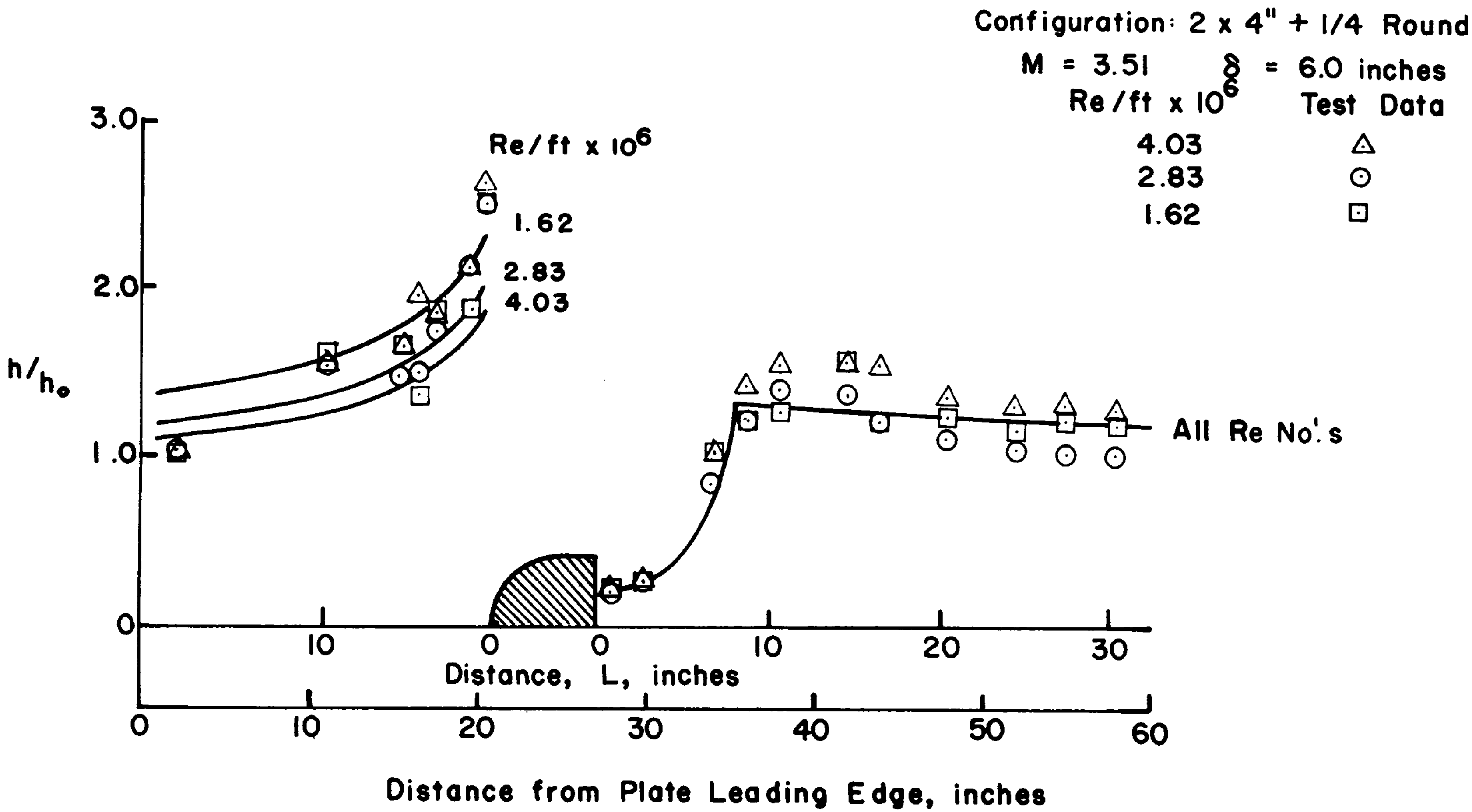

FIGURE 16. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

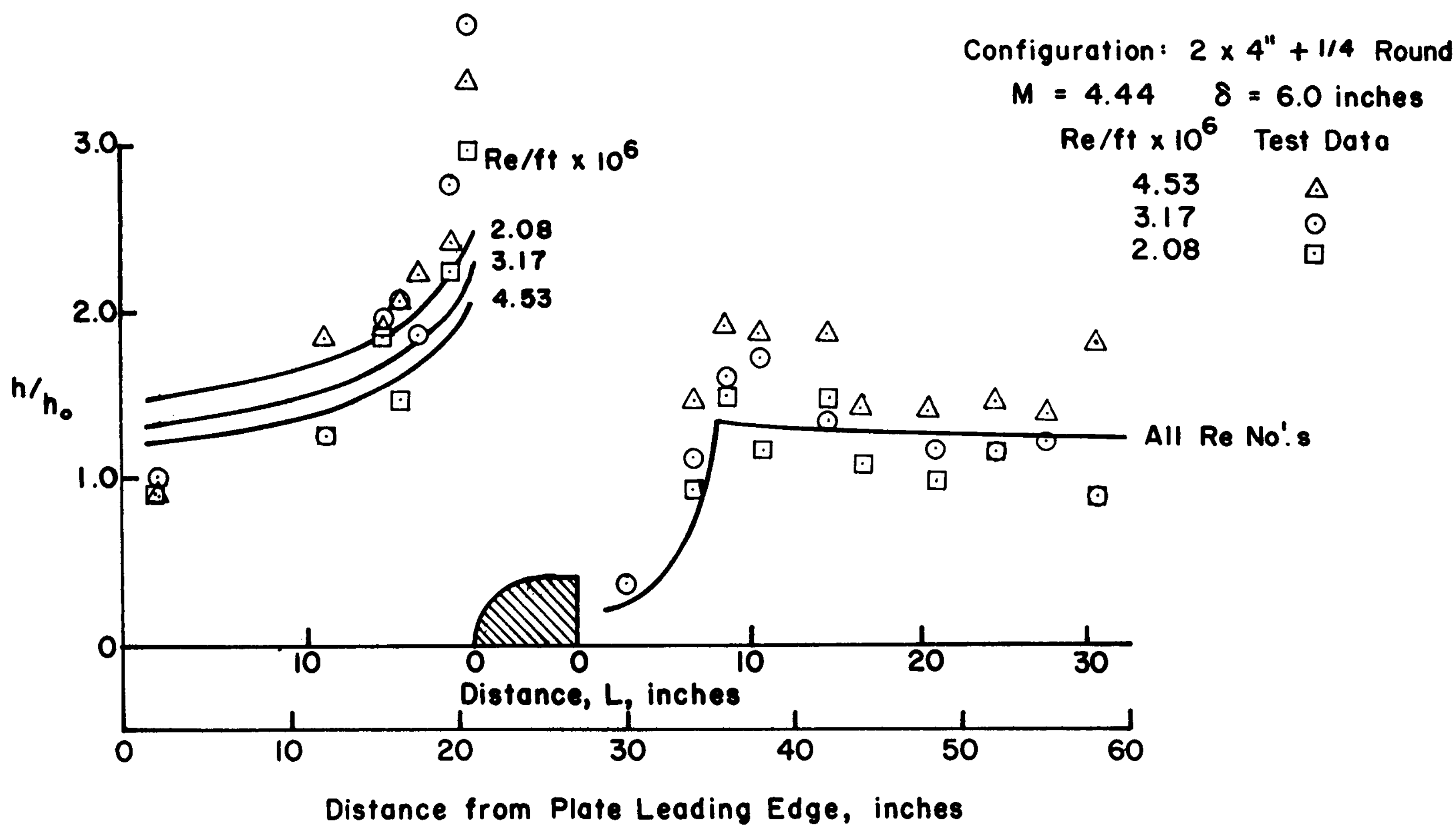

FIGURE 17. COMPARISON OF EXPERIMENTAL TO EMPIRICAL PROTUBERANCE FACTORS

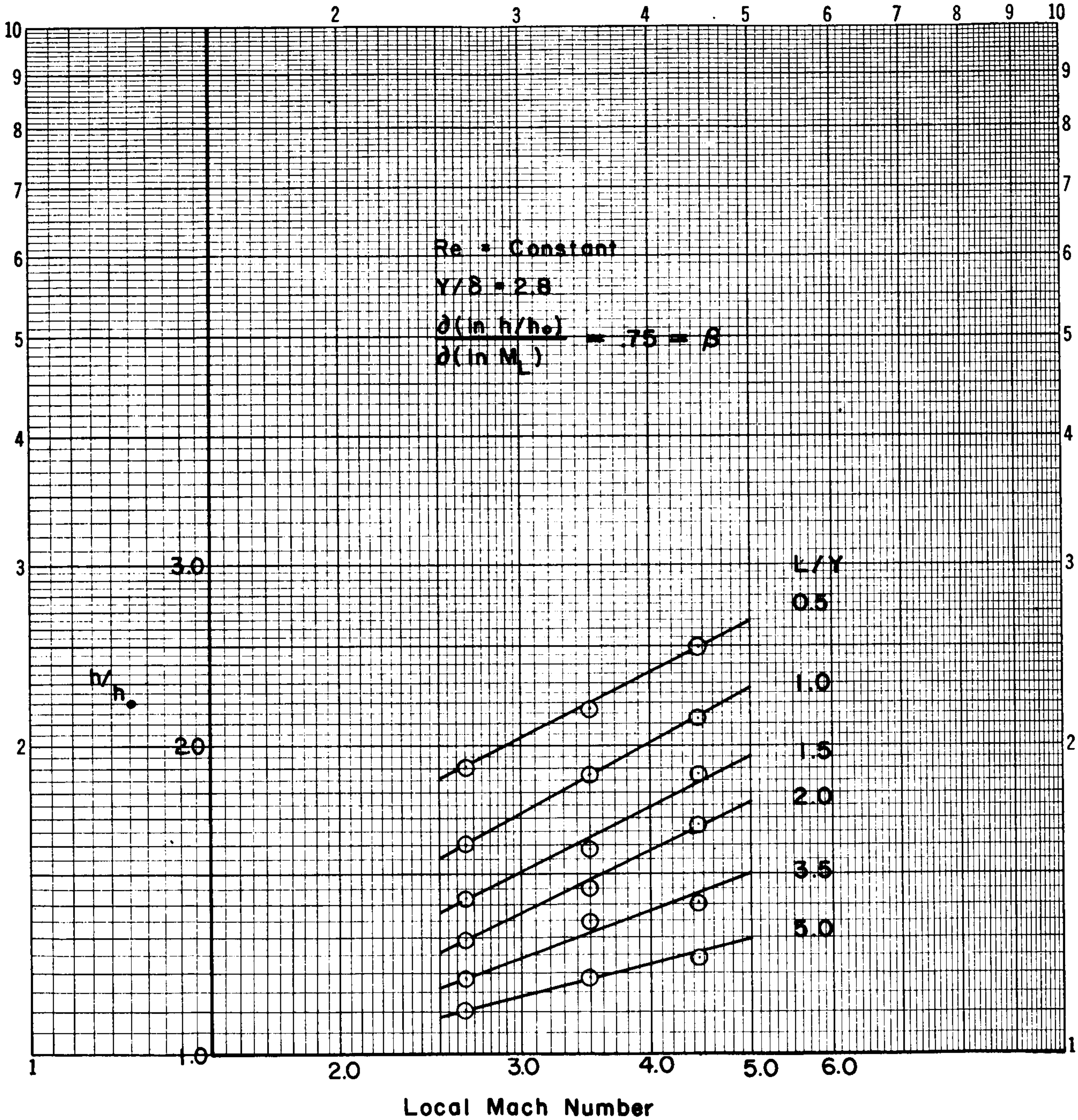

FIGURE 18. DETERMINATION OF COEFFICIENT β FROM EQUATION 3a

APPENDIX

Method of Approach

A study of the data from Reference 3 showed that the dimensionless protuberance factor, h/h_o, depends on four independent variables:

$$h/h_o = f(Re, M_\ell, y/\delta, L/y). \tag{1a}$$

Assuming a product solution of the above parameters, an equation of the following form would result:

$$h/h_o = \emptyset \, Re^{\alpha} M_\ell^{\beta} (y/\delta)^{\gamma} (L/y)^{\xi}. \tag{2a}$$

The exponents α, β, γ, and ξ as well as the constant $\emptyset$, can be determined from the experimental data.

The log of equation (2a) is

$$\ln(h/h_o = \ln \emptyset + \alpha \ln Re + \beta \ln M_\ell + \gamma \ln(y/\delta) + \xi \ln(L/y). \tag{3a}$$

Taking the partial derivative of equation (3a) with respect to each of the variables, holding all the other parameters constant, allowed each exponent to be evaluated. For example

$$\frac{(\partial \ln \frac{h}{h_o})}{(\partial \ln M_\ell)} (\ln Re, \ln y/\delta, \ln L/y)_{constant} = \beta$$

where β can be easily determined by extracting the slope of the curve obtained by plotting h/h_o versus M_ℓ on log-log paper as shown in Figure 18. In this case, β is 3/4. The same operation, performed on all other variables, resulted in the following equation:

$$h/h_o = \emptyset \left[\frac{M^3}{Re(L/y)\ (y/\delta)^2}\right]^{1/4}. \tag{4a}$$

Equation (4a) was formulated using flat-faced protuberance data having δ/y ratios approximately equal to one. Data were available for various δ/y ratios and also for protuberances with other forebody shapes such as a 30-degree wedge and a 1/4-round cylinder.

By adding the factor $y/2 \cot \theta$ to L, equation (4a) would approximate the experimental data for the 30-degree wedge and quarter-round cylinder forebody cases. The $y/2 \cot \theta$ factor merely moved the point from which L was measured back one-half the distance to the original flange origin. The angle θ for the quarter-round cylinder was considered to be 45 degrees.

It was desired to extend the usefulness of the equation to include cases where the protuberance height was either less than, equal to, or greater than the boundary layer thickness. This was done by incorporating by trial and error a δ/y term into the equation. With the evaluation of the constant $\emptyset$ from the test data, the final form of the equation is

$$h/h_o = 60(1.10 - .10\ \delta/y)\left[\frac{M_\ell^3}{Re\left(\frac{L}{y} + \frac{\cot\theta}{2}\right)(y/\delta)^2}\right]. \qquad (5a)$$

The equations for the other two regimes, the separated and reattached areas, were obtained in the same manner as equation (5a), with a similar correction being made for varying δ/y ratio.

REFERENCES

1. Bertram, Mitchel H. and Margarette Wiggs, "Effect of Surface Distortions on the Heat Transfer to a Wing at Hypersonic Speeds," NASA Langley Research Center, Hampton, Va., Volume 1, No. 6, AIAA Journal, June 1963, pp. 1313-1318.

2. Burbank, Paige B., Robert A. Newlander, and Ida K. Collins, "Heat-Transfer and Pressure Measurements on a Flat-Plate Surface and Heat-Transfer Measurements on Attached Protuberances in a Supersonic Turbulent Boundary Layer at Mach Numbers of 2.65, 3.51, and 4.44." National Aeronautics and Space Administration, NASA TN D-1372, December, 1962.

3. Burbank, P. B. and Strauss, H. K., "Heat Transfer to Surfaces and Protuberances in a Supersonic Turbulent Boundary Layer," NACA Research Memo L58E01A, 14 July 1958.

4. Brinich, Paul F., "Recovery Temperatures and Heat Transfer near Two-Dimensional Roughness Elements at Mach 3.1," NACA TN 4213, National Advisory Committee for Aeronautics, February 1958.

5. Bloom, M. H. and A. Pallone, "Heat Transfer to Surfaces in the Neighborhood of Protuberances," 1957, Heat Transfer and Fluid Mechanics - reprints of papers. ASTIA AD-118 138.

6. Lee, Dorothy B. and Maxine A. Paget, "Charts Adapted from Van Driesti Turbulent Flat Plate Theory for Determining Values of Turbulent Aerodynamic Friction and Heat Transfer Coefficients," NACA TN 3811, October 1956.

7. Dunn, Michael G., "Effects of Three-Dimensional Roughness Elements on Boundary-Layer Transition and Aerodynamic Heating," Journal of Spacecraft and Rockets, Volume 1, Number 1, January-February 1964, pp. 68-72.

8. Seba, R. A., "Heat Transfer and Flow with Separated and Reattached Boundary Layers as Produced by Surface Irregularities," University of California at Berkley, Rept. No. WADC TR 56-217, 25 p., ASTIA AD-110 447, May 15, 1956.

9. Wisniewski, R. J., "Turbulent Heat Transfer Coefficients in the Vicinity of Surface Protuberance," NASA Memo 10-1-58E, October 1958, Lewis Research Center, Cleveland, Ohio.

10. Lockheed MSC-SB-61-28, "Aerodynamics of Cones and Protuberances," (an annotated bibliography), May 1961.

11. Rom, Josef, and Arnan Seginer, "Laminar Heat Transfer to a Two-Dimensional Backward Facing Step from the High-Enthalpy Supersonic Flow in the Shock Tube," AIAA Journal, Vol. 2, Number 2, February 1964, pp. 251-255.

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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